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which techniques will prove most useful for problems of this size To be prepared for the WOCE hydrographic data set, it is proposed to start a cooperative (comunity) effort to use these data in a systematic way

An comparison of different existing techniques can be a first step in this direction A number of participants were actively interested in being involved The data set is available to all participants, and also to other interested parties (contact C. Wunsch at MIT, or the mailing list WOCE INVERSDE on telemail OMNET.OCEAN) It is expected that many other fields will be made available, through collaborative effort, in appropriately gridded form These would include transient tracers, carbon related fields, improved estimates of the wind field during the period, and surface color measurements The group agreed to share data as well as model results and code. The participation of other scientists is welcomed

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Fukumori, I., F. Martel, and C. Wunsch, *The* Hydrography of the North Atlantic in the Early 1980's: An Atlas, unpublished document, 1989

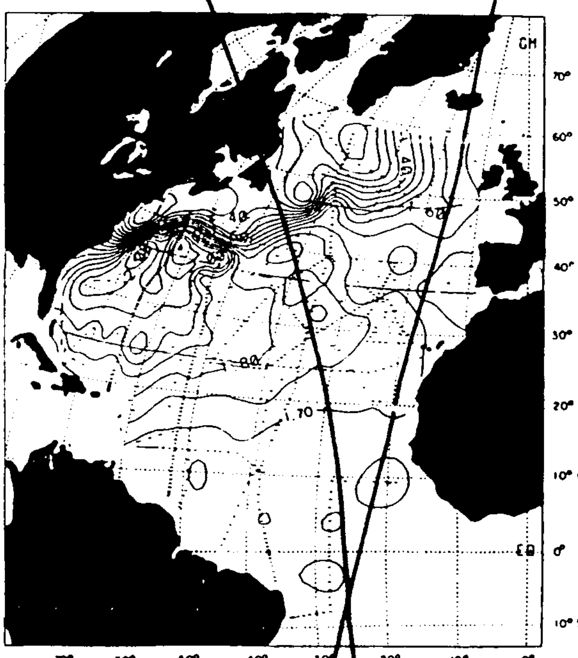

Fig. 2a

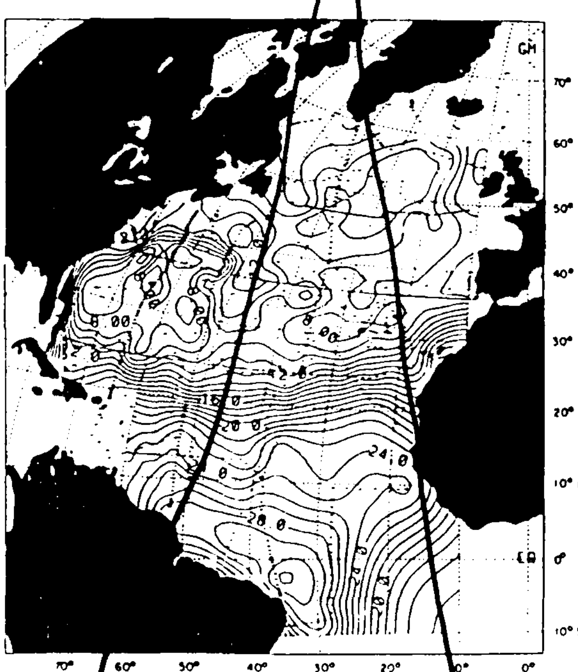

Fig. 2b

Fig. 2. Top. Dynamic topography at 250 dbar relative to 3000 dbar. Contour interval is 5 dyn cm; bottom, Silicate at the 700-m level. Contour interval is 1 micro mole per liter. The maps are part of an atlas containing an analysis of hydrographic observations from 1981-85 [*Fukumori et al.*, 1989]

Coupled Ocean-Atmosphere Models

21st International Liege Colloquium on Ocean Dynamics

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Global-scale ocean dynamics related to El Niño-Southern Oscillation (ENSO) was the focus of the 21st International Colloquium on Ocean Dynamics ENSO provides modelers a great deal of data revealing correlation between sea surface temperature (SST) anomalies and atmospheric pressure differentials in the tropics. (See *Enfield* [1989] for an excellent review of the data.)

The meeting was held May 8-12, 1989, at the University of Liege, Belgium More than 50 scientists attended, from Australia, Belgium, Canada, Federal Republic of Germany, France, Hungary, Italy, Japan, Netherlands, People's Republic of China, Spain, U.K., U.S., and U.S.S.R.

The 16th Colloquium, in 1984

The 1989 colloquium followed one on the same theme in 1984 To give context for the 1989 meeting it is helpful to summarize the earlier one. In 1984 the 16th International Liege Colloquium on Ocean Dynamics was the first meeting to be devoted to coupled ocean-atmosphere models [*Nihoul*, 1985] The motivation for the meeting was, in large part, the very strong El Niño of 1982-1983.

At the 1984 colloquium, 43 scientists presented papers. Almost 30 addressed ocean response to speficied atmospheric forcing or vice versa. Only 2 attempted to couple oceanic and atmospheric general circulation models (GCMs). The modeling state-of-the-art at that time was not ready to attack a benchmark on the scale of the ENSO cycle. One problem that became evident in coupled GCMs was a discouraging downward climate drift in SST and air temperature. On the whole, the field of interactive ocean-atmosphere modeling in 1984 was in its infancy, despite years of experience with separately developed atmospheric and oceanic GCMs

The 21st Colloquium, in 1989

At the 1989 Liege colloquium 32 papers were presented, with about 40% addressing or using ocean-atmosphere coupling parameters. R. W Stewart of the University of Victoria, British Columbia, Canada, opened the meeting on the optimistic note that ocean models are now approaching the point where predictions are possible. He said that political decision makers will take action based on this predictive capability and that it is incumbent on the research community to express the level of uncertainty that exists in the predictions. As the conference progressed, it became clear that his assessment of predictive capability was optimistic and his warning of uncertainty well founded.

The papers given during the first half of the meeting dealt primarily with responses of one medium to the other, with little concern for coupled interaction. The stated theme of the meeting was coupling, so the importance of the first half was to identify the relevant physics and numerics rather than present specific results.

Scientists giving papers in the second *half* of the meeting reported varying degrees of success in modeling the ocean and atmosphere together Some findings will be cited here because of their importance to the coupling issue About 5 of the modeling papers addressed ENSO directly Some promising signs in the model results appeared in the form of eastwardly propagating SST anomalies with time scales of order 2 years for crossing the Pacific Ocean.

Atmospheric Dynamics

Papers on the first day dealt largely with atmospheric response to El Niño. Warm SST anomalies have two immediate effects on the atmosphere above them: increased latent heat flux, and increased convergence Since atmospheric motion is in very delicate balance in the tropics due to the prevalence of convection and the absence of geostrophic control, *the warm SST anomalies quickly induce* broad-scale convergence of surface air This convergence intensifies convective updrafts, causing increased condensation and, ultimately, precipitation

Condensation liberates heat, which intensifies the surface convergence. Hence, increased precipitation generally follows centers of SST warming It is the convergence of surface air that is primarily responsible for the increased precipitation, rather than the simple increase in latent heat flux that comes from warmer SST E Rasmusson of the University of Maryland, College Park, described available data on ENSO and stressed the need to understand phase correlations evident in annual, biennial and lower frequency (4 to 5 year periods) modes of atmospheric variability

The mechanism by which equatorial atmospheric responses propagate from the tropics to midlatitudes is not clear In fact, not all model calculations propagate the response at all When propagation occurs, it does so primarily in response to warm anomalies One suggested propagation mechanism involves the interaction of equatorially induced convergence with the jet stream The suggestion is that the equatorial convergence interrupts the zonal pattern of the jet stream, increasing its wave number and making it more meridional in nature.

In time, increased equatorial convection leads to increased cloudiness and increased outgoing radiation Radiation is the least understood and most complicated heat-transfer process to calculate in the atmosphere, so it is the weakest component of atmospheric models Since radiation plays such an important role in tropical atmospheric motion, atmospheric models suffer in this region of the world.

Fortunately, the other atmospheric processes have been simulated numerically for more than 3 decades in numerical weather prediction (NWP) models for the midlatitudes Virtually all modern atmospheric models used for large-scale air-sea interaction research use the "primitive equations" (PE) of atmospheric motion Such models adequately simulate the relevant physical processes, with the exception of radiation

Ocean Dynamics

In contrast to a long history with atmospheric PE models, ocean models are relatively newer The basic PE ocean model currently in use for research was developed by *Bryan* [1969] A majority of the conference papers about large-scale ocean simulation used one of the variants of this model Other models in use make physical simplifications typified by approaches such as geostrophy, "quasi-geostrophy," lumped-parameter "box ocean" approaches, and one-or two layer Layer models relate ocean evolution to horizontal motion within vertically homogenized layers, with moving layer boundaries describing the ocean surface and thermocline.

Ocean models respond to surface winds and to evaporation and precipitation differences Wind stress provokes the quickest ocean responses, with time scales down to less than an hour—during passage of a storm, for example On the other extreme, the global thermohaline circulation operates on a much longer time scale. This circulation transports the ocean's heat horizontally and is driven by density anomalies that can be due to differential heating, evaporation and precipitation, or vertical mixing. The global thermohaline circulation time is on a decade scale.

Wind increase anomalies have two effects on the ocean: wind-driven currents and mixed-layer deepening Both effects strongly influence ocean circulation The curl of wind stress is the principal factor in large-scale wind-driven ocean circulation Mixed-layer deepening, along with evaporation and precipitation, contributes to the thermohaline circulation

Fresh water input (precipitation and runoff) and evaporation contribute oppositely to mixed-layer processes that drive large-scale circulation currents Evaporation increases mixed-layer salinity Because saline water is more dense than fresh, increased salinity leads to increased convection, mixed-layer deepening and SST cooling. Conversely, when fresh water input exceeds evaporation, the ocean freshens, convection is decreased and the mixed layer shallows. Mixed-layer deepening or shallowing sets up a horizontal pressure gradient that manifests itself in horizontal currents. This process is the principal component of the thermohaline circulation

Two papers described ocean models used to investigate thermohaline currents in the Atlantic and the Pacific, respectively The Atlantic study predicted an inhibiting effect on these currents that results from increased output of the St. Lawrence River. Both studies showed that the existence of dual steady states was plausible, suggesting the possibility that different circulation patterns may have existed in the past

Coupled Interactions

Global-Scale Models Discussion of model coupling began on the third day of the meeting About half the remaining participants discussed true coupling Due to the complicated nature of each individual medium's response to the other, truly coupled models require enormous computer resources or considerable simplification or both The latter greatly compromises reality and the former is very expensive Hence, all the papers on true coupling were filled with introductory qualifications such as "simplification" or "preliminary"

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In this qualifying vein, it is worthwhile highlighting some of these preliminary results relating to SST anomaly propagation. S. Philander and W. Lau of the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, N.J., found that the direction of SST anomaly propagation was sensitive to the resolution of the ocean model. T. Tokioka and colleagues at the Meteorological Research Institute, in Tsukuba, Japan, found eastward propagating SST anomalies with coupled 5-level atmosphere, 14-level ocean models, both having a common horizontal grid resolution of 5° × 4°. K. Bryan of GFDL found SST anomalies slowly propagating eastward in the Atlantic Ocean. He noted that unless a proper balance of moisture flux between ocean and atmospheric models is maintained, the Atlantic's heat transport mechanism is impaired, leading to downward climatological drift eventually terminating in an ice age.

It appears that the models of each medium are sufficiently advanced, the interest in coupling is sufficiently high, and available computer resources are rapidly enough increasing so as to make true couplings attainable. But the present preliminary attempts make the findings still tentative.

Climate Drift. The most persistent of these early findings was that both models exhibit climate drift toward cooling. Ocean and atmospheric GCMs using the PE approach solve their equations (at least in the vertical direction) by finite difference methods. Finite differences implicitly or explicitly introduce numerical diffusion to ensure smoothness and stability of the solution. Since the ocean has a large reservoir of cold water beneath a relatively shallow, warm surface layer, a numerical procedure that mixes this deep large cool reservoir with the shallow warm one tends to lower the surface temperature. This artificial diffusion of subsurface water into the mixed layer is a serious problem for PE ocean models. The atmospheric radiation balance problem also contributes to a cold climatological drift. When ocean and atmospheric models are coupled, this drift accelerates and eventually weakens the coupled system beyond reality.

Other Issues

Many topics other than those mentioned here were discussed at the 1989 Liege colloquium. Two papers dealt with smaller-scale model coupling: one on quasi-steady matching of ocean and atmospheric boundary layers, and one on hurricane dynamics.

Other issues touched on during the conference were polar ice cover, global atmospheric albedo, and the greenhouse effect. Another potentially important topic not covered was the time and space scale mismatch between atmospheric and ocean processes. During question periods, modelers were asked for specifics on how interface conditions are handled in light of this mismatch. Answers were short comments indicating that fluxes are interchanged from one to a few times per day. Apparently, a framework for consistent flux exchange has yet to be investigated. It seems likely that the temporal and spatial scale mismatch between ocean and atmosphere will require special numerical-theoretical methods for proper treating of the interface. The relative importance of these issues will, one hopes, be clarified by work in progress during the next few years.

Summary and Conclusions

Similarities and differences between the first and second Liege colloquiums devoted to ocean-atmosphere coupling show the progress that has been made in the five years between the meetings. Although both were nominally devoted to coupling, both had a minority of papers truly devoted to that topic. The 1989 colloquium made more progress in that direction, but coupling is still a very complicated issue and most investigators prefer the simpler problem of one medium responding to the other with no feedback.

Despite this preference, a number of indicators point in an optimistic direction for coupled modeling. In 1984 the community was hardly ready to attempt serious interactive coupling of GCMs because of limited computer resources and few proven models. Independent ocean and atmospheric modeling has made considerable progress over the past 5 years. Computer resources are considerably greater now than 5 years ago, and excellent global models exist for coupled experimentation.

A few anecdotes help capture of the colloquium. Referring to the history of uncoupled models, one speaker pointed out "improprieties" of "topless oceans" and "bottomless atmospheres." Another speaker compared the ocean-atmosphere interaction to a marriage. The parties to this marriage exchange heat and have periods of elevated stress. At times one member of the partnership is slave to the other, and at other times forces the other into action. Each member of the partnership has its own personality: the atmosphere is impetuous, the ocean rather reserved.

Another speaker pointed out the need for reliable component models with a profound observation: "when two bad models are coupled, it is possible to get a bad result." A more serious summary was given by S. Ineson of the Metrorological Office, Bracknell, U.K., when he said "Coupled modeling is very difficult, but we are making progress."

Because ocean-atmosphere model coupling is a relatively new and uncharted field, ambitious modeling efforts are still in shake down phases. Modelers are generally moving toward qualitative reasonability of results with quantitative accuracy of predictions yet to be determined. In comparison with developments in the component modeling areas, firm conclusions and new insights in coupled ocean-atmosphere modeling are elusive. Within the component models, physics improvement seems to be required in atmospheric radiation simulations, and improved numerics seems to be required to remove numerical diffusion from the ocean models. Larger computers will be required to allow both models to be run in sufficient time and space resolution to include all the relevant processes. Since this latter suggestion contains an element of "brute force," there is an indication of need for more theoretical work on consistent model coupling allowing for disparate time and space scales of the ocean and atmosphere.

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GAP

Atmospheric Composition and Structure

0194 Instruments and Techniques
AN ANALYSIS OF THE 8 YEAR TREND IN OZONE DEPLETION FROM ALTERNATE MODELS OF SBUV INSTRUMENT DEGRADATION
J. R. Herman (Goddard Space Flight Center, Greenbelt, MD 20771)
R. D. Hudson, G. Serafino

Currently archived ozone data from the Solar Backscatter Ultraviolet Spectrometer experiment (SBUV) on the Nimbus 7 satellite has been reported to show large global decreases in the amount of atmospheric ozone, both total content and as a function of altitude, for the period from 1978 to 1987. Analysis of atmospheric albedo data ... with time. Their combined degradation can be obtained from apparent decreases in measured solar irradiance at wavelengths where little or no long term secondary changes are expected. The central problem in analyzing SBUV data is to separately specify the diffuser plate degradation (Hudson et al., 1988). Ratios of radiance to solar irradiance used to obtain ozone amounts are proportional only to diffuser reflectivity and independent of any spectrometer degradation. ... (Ozone trend, SBUV, TOMS)

J. Geophys. Res., D, Paper 89JD03414

0360 Transmission and scattering of radiation
SATELLITE MEASUREMENTS OF LARGE SCALE AIR POLLUTION METHOD
Yoram J. Kaufman (NASA Goddard Space Flight Center, code 613, Greenbelt, MD 20771)
Robert S. Fraser and Richard A. Ferrare

... images of a forest fire smoke. The aerosol optical thickness and particle size derived from the AVHRR images are compared to the analysis of sun photometer measurements from the ground. (Aerosol, remote sensing, Radiative transfer, pollution, scattering of radiation)

J. Geophys. Res., D, Paper 89JD03084

0305 Aerosols and Particles
SATELLITE MEASUREMENTS OF LARGE SCALE AIR POLLUTION - MEASUREMENTS OF FOREST FIRE SMOKE
R. A. Ferrare (Mail Code 613, NASA/Goddard Space Flight Center, Greenbelt, MD 20771)
R. S. Fraser, Y. J. Kaufman

... (Aerosols and particles, Troposphere-composition and chemistry, Pollution-urban and regional)

J. Geophys. Res., D, Paper 89JD03085

0315
SEASONAL DYNAMICS IN METHANE EMISSIONS FROM THE AMAZON RIVER FLOODPLAIN TO THE TROPOSPHERE
Allan H. Devol, Jeffrey E. Richey (School of Oceanography, WB-10, University of Washington, Seattle, Washington 98195)

J. Geophys. Res., D, Paper 89JD01873

PALEOCEANOGRAPHY

Electromagnetics

0659 Random media and rough surfaces
FIRST-ORDER ... EXTENSION ... TO THE ELECTROMAGNETIC SCATTERING BY DIELECTRIC ROUGH INTERFACES

Rad. Sci., Paper 89RS01050

Exploration Geophysics

0935 Seismic methods
INVERSION FOR CRUSTAL STRUCTURE USING REFLECTIONS FROM THE PASSCAL OUACHITA EXPERIMENT

Volume 26 Number 1 January 1990 WATER RESOURCES RESEARCH

Corrections